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Provenance study on Chinese bronze artefacts of E in the Zhou Dynasty by lead isotope analysis

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ABSTRACT

Lead isotope ratios of eight Chinese bronze artefacts from the Xiaxiangpu site (Nanyang City, Henan Province) were analysed and compared with those of natural ores and other Chinese bronze artefacts. This study attempts to find out the isotopic characteristics of bronze artefacts from the late Western Zhou to the early Eastern Zhou period by taking the bronzes of E as an example. Another important aspect of the study is to test whether there is an associated signature for bronze production between the state of E and the Zhou royal court or other vassal states. The political and economic status of E and other vassal states in the turn of the Western Zhou Dynasty to the Eastern Zhou Dynasty is also within the scope of the study. The elemental concentrations suggest the lead should be introduced on purpose, and the lead isotopes represent the provenance information of lead ores. The results of lead isotope analysis show that the lead isotope ratios conform to the characteristics of common lead. As the isotope ratios of the eight samples are quite close to each other, all these samples may share a common lead ore source. The lead ore deposits around Chengxian County seem to be the most likely sources of lead which was mined and used for making the Xiaxiangpu bronzes. According to historical documents, the state of E was defeated by troops from northwest China. The comparison of the Xiaxiangpu bronzes with bronze artefacts from Gansu Province, Shaanxi Province and Shanxi Province shows many overlaps. After the state of E lost its power, it might have become economically subservient to the states in the northwest. Therefore, the states in northwest China had the opportunity to keep growing.

1. Introduction

1.1. The history of the state of E

The state of E was first documented in the oracle bone inscriptions, which traced back to the period of King Wuding in the Shang Dynasty (c. 1250–1192 BC). According to the oracle bone inscriptions, the Shang royal court held sacrificial rites and hunting activities in the E region. In the period of King Zhou (c. 1105–1046 BC), the leader of E had already enjoyed the title of marquis. Marquis E was one of the Three Lords, which were highly valued by the king and other vassals. In the Western Zhou Dynasty (c. 1046–771 BC), the nobility of the Zhou royal family and the nobility of E were related by marriage. The state of E was once an important military barrier of the Western Zhou against the minority nationalities in the Huai River Valley. But in the period of King Li (c. 878–841 BC), the state of E united with the minority nationalities in the Huai River Valley. They rebelled against the Western Zhou Dynasty but ended in failure. The family of E was massacred at the defeat, and no written records about the state of E were ever found since then. However, as the archaeological excavation at the Xiaxiangpu site has shown, the state of E survived the war in the late Western Zhou Dynasty, and the highest leader of E might still keep his title of Marquis (Ding and Fang, 2010; Li, 2008; Xu, 1994).

When time shifted from the Western Zhou to the Eastern Zhou, the Zhou royal family declined, and the vassal states were gradually

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getting stronger (Ye, 2005; Xu, 2004; Zhou, 2002). The following two historical questions emerged:

(1) Although the leader of E might still keep his title of Marquis, had the state of E been weakened after the war? Did it get stronger as the other vassal states? Or did it decline with the Zhou royal family?
(2) Under the new and changed situation, did the state of E associate with the Western Zhou royal family or the other vassal states? Was there any material evidence for the political or economic unions?

1.2. Lead isotopic studies on Chinese bronzes

Lead isotopic signatures have been widely adopted in provenance studies of bronze artefacts in the field of archaeometallurgy. The lead isotopic signatures are used as finger-prints to hopefully generate information about the sources of bronze raw materials (lead in mineral form in particular). Since the ratios of lead isotopes do not change during metallurgical processes or chemical reactions, searching the source of lead in bronzes can be relatively easy if a quite good sample of both bronze artefacts and lead ores can be studied and compared geochemically and a good understanding of local or regional geological mines is reached. The method has been so far considered by many as the most powerful tool to reveal the possible geological sources for bronze casting in early China. Besides, human activities involved from the procurement of lead ores to the production of bronzes also help us develop a better understanding of the sociopolitical and economic organizations (Cattin et al., 2009; Cui and Wu, 2008; Jin, 2008; YIGMR, 1979).

Lead isotope analysis was first introduced into Chinese archaeology in 1980s, and has been used as a primary approach to search the possible sources of ores for bronze production in ancient China ever since. Provenance studies on Chinese bronzes began with the discovery of Shang bronzes with high radiogenic lead isotope compositions in Henan Province. The $^{207}Pb/^{206}Pb$ ratios of these Shang bronzes mostly lie between 0.70 and 0.78. Compared to Shang bronzes, Chinese galena ores generate higher $^{207}Pb/^{206}Pb$ ratios (usually higher than 0.84) (Tian et al., 2010; Jin, 2008; Zhu and Chang, 2002). Further researches brought up the theory that bronzes with low $^{207}Pb/^{206}Pb$ ratios disappeared gradually in the Zhou Dynasty (Jin, 2008; Li, 2002). There are separate researches on the bronzes with common lead from the Western Zhou Dynasty in Beijing, Shaanxi and Shanxi Province (Nan and Ma, 2012; Jia, 2010; Li, 2010; Jin, 2008; Peng et al., 1988), but bronzes from Henan Province have not been studied yet. Therefore, it is hard to tell whether the Zhou people's losing interest or access to lead with low $^{207}Pb/^{206}Pb$ ratios and the use of lead with higher $^{207}Pb/^{206}Pb$ ratios in bronze production occurred simultaneously, and if it did appear so, how did that happen.

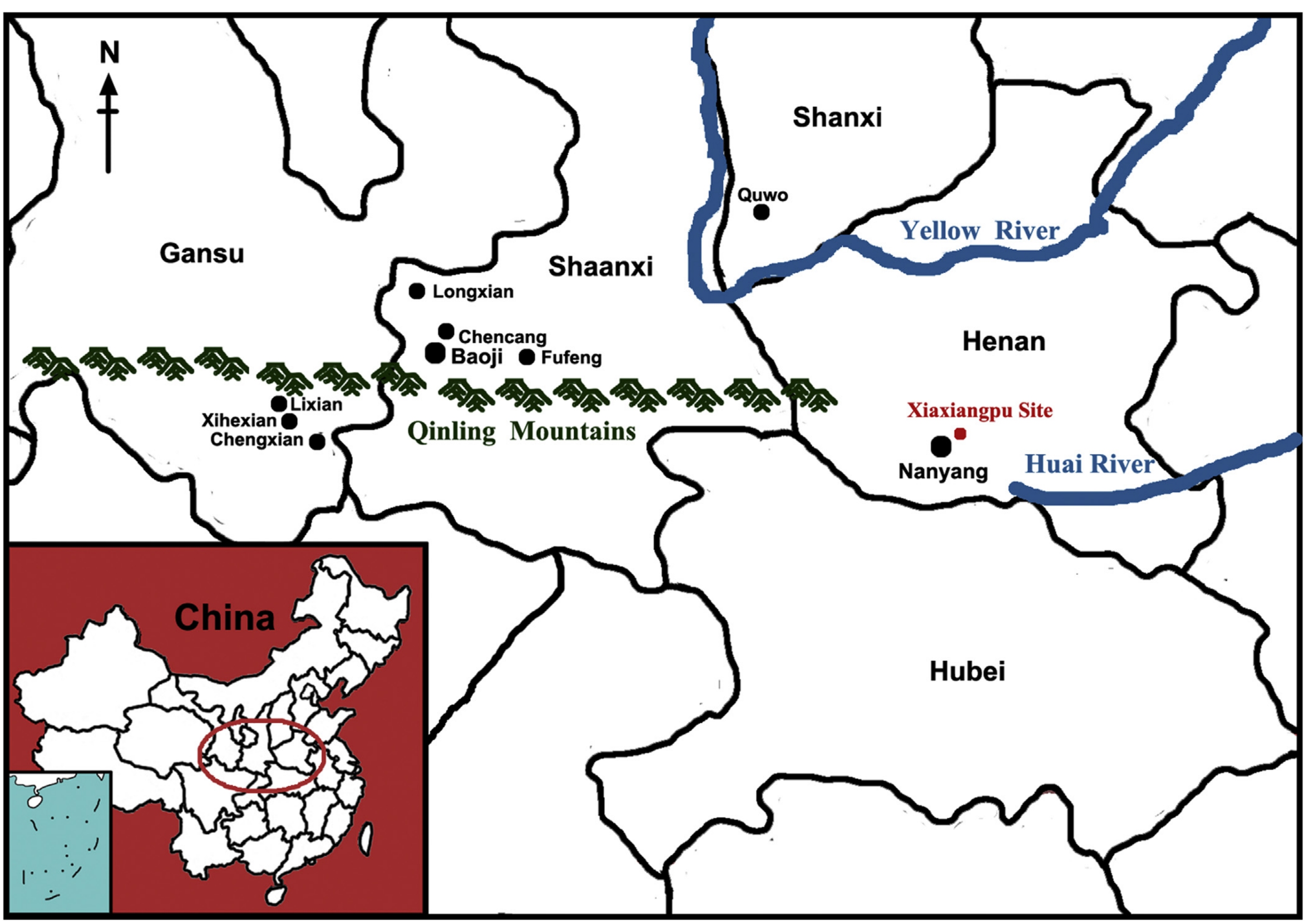

Fig. 1. A sketch map for the main area discussed. Province Henan, Hubei, Shanxi, Shaanxi, Gansu are shown from east to west, the Xiaxiangpu site is in the south part of Henan. The Qinling Mountains, the Yellow River and the Huai River are also shown in the map as geographical dividing lines.

In the turn of the Western Zhou Dynasty to the Eastern Zhou Dynasty, status and power of the Zhou royal family and the vassal states had been dramatically changed. According to historical documents, the militant influence of some vassal states grew significantly in this period, such as the states of Qin, Jin, Qi and Chu (Ye, 2005; Xu, 2004; Zhou, 2002). Lead isotopic studies of bronze artefacts made and used during this period are usually focussing on bronzes from the states of Qin and Jin whose power had been demonstrated in the most intense sense within the present-day Shaanxi and Shanxi provinces. In these lead isotopic studies, lead isotope ratios of the bronzes always show local characteristics. It suggests that the bronzes of Qin and Jin might be locally made (Jia, 2010; Jin, 2008). Though these studies put forward the evidence that Qin and Jin might not rely on import bronzes, whether Qin and Jin had the ability to export bronzes is still an open question. Lead isotopic studies of bronzes from ancient vassal states related to Qin and Jin may provide a fresh perspective on this issue.

1.3. Research aims

The aim of this study is to investigate the provenance of bronzes of E from the Xiaxiangpu site. This study is a proxy for better understanding the history of E and its sociopolitical and economic interactions with near and more distant neighbours in the turn of the Western Zhou Dynasty to the Eastern Zhou Dynasty (c. 885–650 BC). By testing the possible provenance of the ores used for the bronzes of E, the specific objectives could be predefined as follows:

(1) To find out lead isotopic composition characteristics of bronze artefacts in the late Western Zhou Dynasty to the early Eastern Zhou Dynasty by taking the bronzes of E as an example.
(2) To test whether there is a common signature for bronze production between the state of E and the Zhou royal court or other vassal states.
(3) To shed some light on the political and economic status of the state of E in the turn of the Western Zhou Dynasty to the Eastern Zhou Dynasty.

2. Materials and methods

2.1. Archaeological contexts and samples

This study is based on a collection of eight archaeological bronzes of the state of E in the late Western Zhou to the early Eastern Zhou Dynasty (c. 885–650 BC). The bronze artefacts have been selected from the Xiaxiangpu site. The site is located about 1 km north of the Xiaxiangpu Village, Xindian Town in Nanyang City, Henan Province, and was first excavated in the summer of 2012 (Figs. 1, 2). This archaeological excavation was carried out by the Institute of Cultural Relic Research of Nanyang City. 20 tombs were excavated, with most of the material remains being pieces of bronze vessels. Information about the samples is listed in Table 1 and shown in Fig. 3.

Ding, Gui, Hu, Zun, Li, Pan and Yi vessels were always found together. The Ding vessels are with vertical abdomens and hoof-like legs, and the Gui vessels are with inward rims and covers. The decorations on the bronze artefacts are in geometric pattern (Figs. 4, 5). All these elements are similar to those on bronze artefacts that were used by the Zhou royal court. Sample XXP01 and sample XXP02 were from the Tomb M1 (Fig. 5). Seven Ding vessels from M1 were produced in the same shape and decorative pattern but in different sizes. Six of the seven Ding vessels had the inscriptions of “Marquise E”. Archaeologists regard M1 as a tomb of the wife of a leader of E. XXP03 was from M5, XXP04 and XXP05 were from M6 (Fig. 5). M5 and M6 were in the same couple-burial unit. Numbers of bronze sacrificial vessels and bronze weapons were found in this unit. XXP06 was from M16 (Fig. 5). Two sealed Hu vessels were found in M16. It is supposed that there should be liquids inside. XXP07 was from M19, and XXP08 was from M20 (Fig. 5). M19 and M20 were in the same couple-burial unit. Owners of M19 and M20 belonged to the nobility of E. Lots of sacrificial vessels were excavated from the two tombs.

2.2. Energy dispersive X-ray fluorescence spectroscopy

Small pieces of bronze samples were inserted into bakelite cylinders by a metallographic inlaying machine (XQ-1, SMEC Ltd., Shanghai, China). We carried out XRF analyses at the Institute of High Energy Physics, Chinese Academy of Sciences in Beijing. The elemental compositions were determined by a laboratory micro-XRF system (Eagle-III microprobe, EDAX Inc., NJ, USA). The spectrometer is equipped with a micro focus X-ray tube with an Rh anode and an 80 mm^2 energy dispersive Si (Li) detector. A spot size of 100 μm was chosen at an operating X-ray tube voltage of 40 kV. The software employed for spectrum retraction and analysis is the programme Vision32, associating with the instrument. The standard sample utilized is a standard reference material, GBW02137, developed by CRM/RM Information Center of China. Table 2 gives the results obtained and the certified values. The overall relative error is less than 6.29%.

Fig. 2. A sketch map for the Xiaxiangpu site.

Table 1
Archaeological descriptions of the analysed bronze artefacts.

Number	Burial unit	Type	Number	Burial unit	Type
XXP01	M1	A bronze piece	XXP05	M6	A bronze piece
XXP02	M1	A piece of a Ding vessel	XXP06	M16	A piece of a bronze fish
XXP03	M5	A bronze piece	XXP07	M19	A piece of a Hu vessel
XXP04	M6	A bronze piece	XXP08	M20	A piece of a Ding vessel

2.3. Lead isotope ratios determined by MC-ICP-MS

Lead isotope analyses were carried at the School of Archaeology and Museology, Peking University in Beijing. Firstly, about 2 mg of bronze pieces were chipped off. The pieces were then dissolved in 3 ml of HCl and 1 ml of HNO_3. Later, the clear solution was leached and diluted with deionized water to 10 ml. The solutions were then measured to detect the lead contents by ICP-AES (PHD, Leeman Labs Inc., California, USA). According to the results representing the lead contents, the solutions were diluted to 1000 ppb. The thallium (T1) standard SRM997 was added in the solutions. Lead isotope analyses were carried out by a MC-ICP-MS (VG AXIOM, Thermo-Elemental Inc., Winsford, England). The spectrometer is a double focussing magnetic sector instrument equipped with an array of 10 variable Faraday collectors. And it has a further fixed Faraday and an electron multiplier detector. Based on repeated analysis of SRM981, the overall analytical 2σ error for all lead isotope ratios is less than 0.826% (Table 3). The results are in good agreement with published values (Cattin et al., 2011). The model ages are estimated after Holmes and Houtermans (1946) (YIGMR, 1979).

3. Results and discussion

3.1. Elemental concentrations and lead isotopic composition characteristics

Elemental concentrations of the bronze samples are given in Table 4. In Table 4, the lead concentrations of the samples are all higher than 3%. There are two assumptions about the introduction of lead: (1) Lead should be introduced by copper ores if the lead content is between 50 ppm and 4% (Gale and Stos-Gale, 2000); (2) Lead should be introduced by copper ores if the lead content is below 2% or 3% (Qin et al., 2004). Lead content of XXP03 and XXP05 is between 3% and 4%, while other six samples are all over 5% (Table 4). It suggests the lead should be added on purpose, and the lead isotopes point to the source of lead ores.

The obtained Pb isotope compositions for the Xiaxiangpu bronzes are given in Table 4. The $^{206}Pb/^{204}Pb$ ratios range from 17.906 to 18.013, $^{207}Pb/^{204}Pb$ ratios from 15.498 to 15.576, and $^{208}Pb/^{204}Pb$ ratios from 38.140 to 38.329. The differences are less than 0.2. Pb model ages of the samples are between 423 million years and 493 million years. In view of these characteristics, these isotope ratios conform to the characteristics of common lead. The $^{207}Pb/^{206}Pb$ ratios range from 0.865 to 0.867. It supports the assumption that bronzes with low $^{207}Pb/^{206}Pb$ ratios between 0.70 and 0.78 disappeared gradually during the Zhou Dynasty in Henan Province (Tian et al., 2010; Cattin et al., 2009; Cui and Wu, 2008; Jin, 2008; Zhu and Chang, 2002).

To help understand the significance of the isotope results for the artefacts, certain reference data have been plotted in Fig. 6. These isotopic compositions plot in the overlapping area of lower crust, mantle and orogenic fields, indicating crust-mantle mixing lead (Fig. 6) (Zartman and Doe, 1981). The isotope ratios of the eight

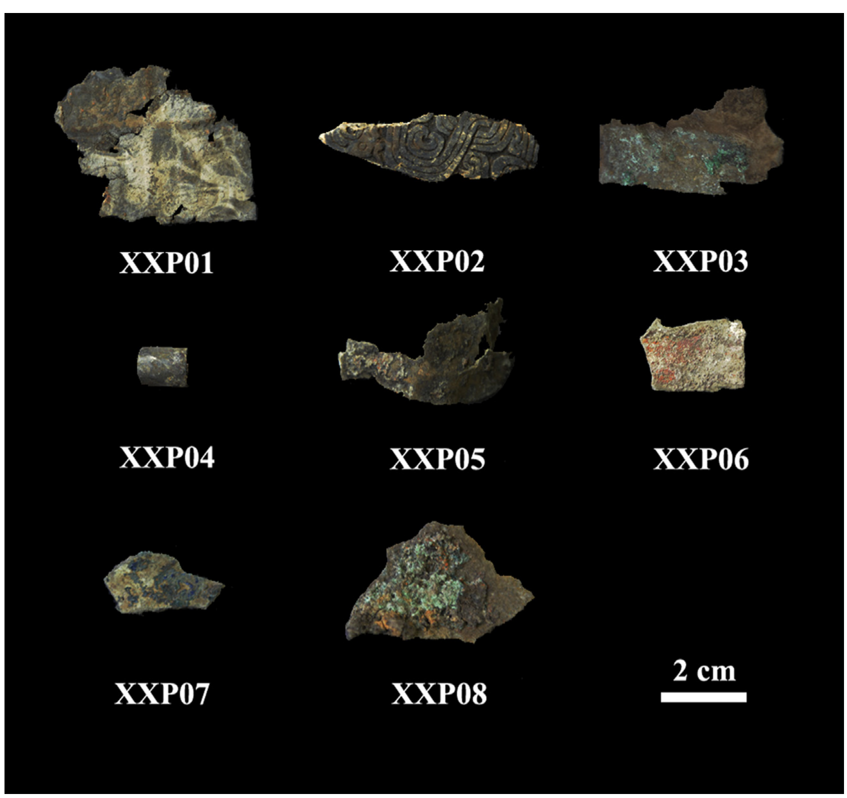

Fig. 3. Photographs of the bronze pieces from the Xiaxiangpu site used as samples, described in Table 1.

Fig. 4. Photographs of typical bronze sacrificial vessels excavated at the Xiaxiangpu site.

samples concentrate in Fig. 6. Thus, all these samples may have a single lead ore source. Two samples, namely XXP05 and XXP07, are close together in Fig. 7 in an area which is distinct from the group of the other six samples, namely, XXP01, XXP02, XXP03, XXP04, XXP06 and XXP08. It seems possible that these samples might have two lead ore sources, one for XXP05 and XXP07, and another for the other six samples. However, in consideration of the fact the lead isotope ratios concentrate on Fig. 6, even if the eight samples have two lead ore sources, the lead isotope ratios of the two deposits are similar to each other.

3.2. Provenance studies

The lateral variation between different terranes is greater than the vertical variation between crust and mantle, which has already been proved by the comparison of lead isotopic compositions of various ores and rocks. Sharp lead isotope transitions can show the geochemical boundaries of a certain district. Therefore, lead isotope is a powerful tool for recognizing geochemical province study. There are six geochemical provinces in China based on lead isotopic compositions, namely Northern China, Yangtze, Southern China, Northern Xinjiang, Jiamusi and Tibet (Zhu, 1995; Zartman, 1974).

For the geochemical province Southern China, both Th-derived and U-derived isotopes are rich in crust and mantle: The lead isotopic compositions display a range of values above 18.3 for $^{206}Pb/^{204}Pb$ ratios, above 15.5 for $^{207}Pb/^{204}Pb$ ratios, and above 38.4 for $^{208}Pb/^{204}Pb$ ratios. The range of lead isotopic compositions of the geochemical province Yangtze is narrow: The lead isotopic compositions display a range of values from 17.5 to 18.2 for $^{206}Pb/^{204}Pb$ ratios, from 15.55 to 15.6 for $^{207}Pb/^{204}Pb$ ratios, and from 37.5 to 39.0 for $^{208}Pb/^{204}Pb$ ratios. For the geochemical province Northern China, Th-derived isotopes are rich and U-derived isotopes are poor: The lead isotopic compositions display a range of values from 13.5 to 17.8 for $^{206}Pb/^{204}Pb$ ratios, from 14.44 to 15.48 for $^{207}Pb/^{204}Pb$ ratios, and from 33.1 to 41 for $^{208}Pb/^{204}Pb$ ratios (Zhu, 1995). The lead isotopic compositions of the bronzes from the

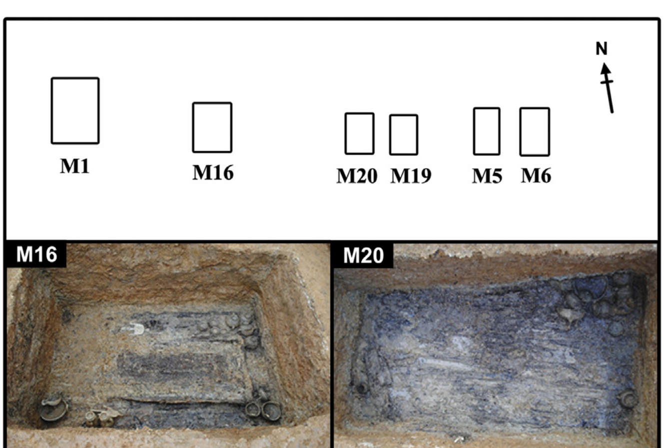

Fig. 5. Photographs of typical tombs at the Xiaxiangpu site. The distribution of the tombs is also shown.

Table 2
Comparison of elemental concentrations measured in GBW02137 and the certified values. The relative error is also shown.

Elemental concentrations (Wt %)	Cu	Pb	Sn	Zn
Measured values	86.02	3.09	5.97	4.92
Certified values	85.16	3.25	5.69	5.25
Relative error (%)	1.01	4.92	4.92	6.29

Table 3
The results of two runs for the SRM981 determination, analytical 2σ error and published values from Cattin et al. (2011).

Number	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$
1	16.940	15.493	36.700	0.915	2.166
2	16.941	15.495	36.705	0.915	2.167
Analytical 2σ error (%)	0.120	0.199	0.826	0.005	0.033
Cattin et al. (2011)	16.942	15.496	36.720	0.915	2.167

Table 4
Elemental concentrations, lead isotopic compositions and model ages of the samples.

Number	Elemental concentrations (Wt %)			Lead isotopic compositions				Model ages
	Cu	Sn	Pb	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	(M.Y.)
XXP01	73.8	15.8	5.8	18.002	15.576	38.283	0.865	430
XXP02	73.3	15.7	7.4	18.006	15.571	38.254	0.865	427
XXP03	76.2	17.5	3.8	18.013	15.574	38.310	0.865	423
XXP04	60.6	14.7	5.9	18.006	15.568	38.329	0.865	427
XXP05	80.7	13.9	3.2	17.907	15.516	38.140	0.867	493
XXP06	72.9	12.9	12.9	17.976	15.562	38.223	0.866	447
XXP07	74.3	11.0	13.1	17.906	15.498	38.181	0.866	493
XXP08	75.9	5.0	17.9	17.960	15.563	38.207	0.867	458

Xiaxiangpu site display a range of values from 17.906 to 18.013 for $^{206}Pb/^{204}Pb$ ratios, from 15.498 to 15.576 for $^{207}Pb/^{204}Pb$ ratios, and from 38.140 to 38.329 for $^{208}Pb/^{204}Pb$ ratios, which seen all agree with the geochemical province Yangtze (Fig. 8).

The buffering zone of geochemical province Yangtze includes most of the Yangtze Block, and western Qinling and southern Tianshan Mountains (Zhu, 1995). The ratios of all eight samples are consistent with lead ore isotopes from the Dengjiashan lead deposit and the Lijiagou lead deposit (Fig. 9) (Qi, 1993). The lead isotope ratios of Dengjiashan and Lijiagou lead deposits are in accordance with the single stage evolution model (Qi, 1993). And these isotope ratios share the characteristics of crust–mantle mixing lead (Wang et al., 2013). Pb model ages of Dengjiashan lead deposit are between 410 million years to 481 million years, and 362 million years to 464 million years for Lijiagou lead deposit (Qi, 1993). All these characteristics are similar to the lead isotopic composition characteristics of the eight samples. The Dengjiashan lead deposit is located in Xihexian County, and the Lijiagou lead deposit is located in Chengxian County. Xihexian County and Chengxian County are both in Longnan City, Gansu Province (Fig. 1). The Dengjiashan lead deposit and Lijiagou lead deposit are both in the Xihexian–Chengxian metallogenic belt, which is one of the important producers of Pb–Zn in the Qinling Mountains belt. The lead isotope ratios of galena minerals from the Xihexian–Chengxian metallogenic belt are unique all over China (Wang et al., 2013; Qi, 1993). The ratios of XXP05 and XXP07 closely match those from the Lijiagou lead deposit on the $^{206}Pb/^{204}Pb$–$^{207}Pb/^{204}Pb$ plots, while the ratios of the other six samples most closely match the Dengjiashan lead deposit (Fig. 9). Th-derived isotope ratios of the ores from Dengjiashan lead deposit are generally lower than the Xiaxiangpu bronzes. Th-derived isotope ratios of the ores from Lijiagou

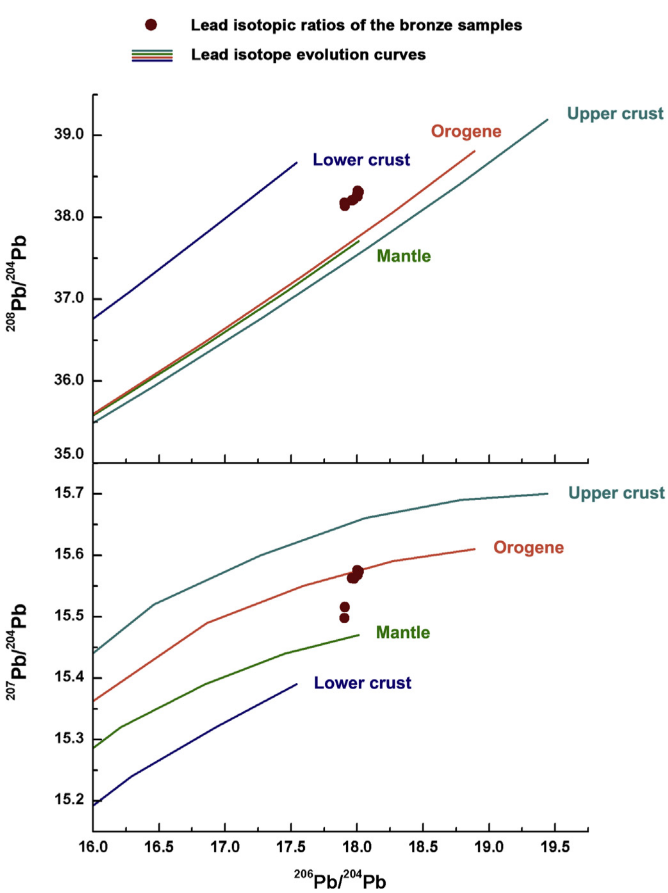

Fig. 6. Comparison diagram based on the summary plots of lead isotope ratios used to define the modern fields for mantle, upper crust, lower crust and orogene (after Zartman and Doe, 1981).

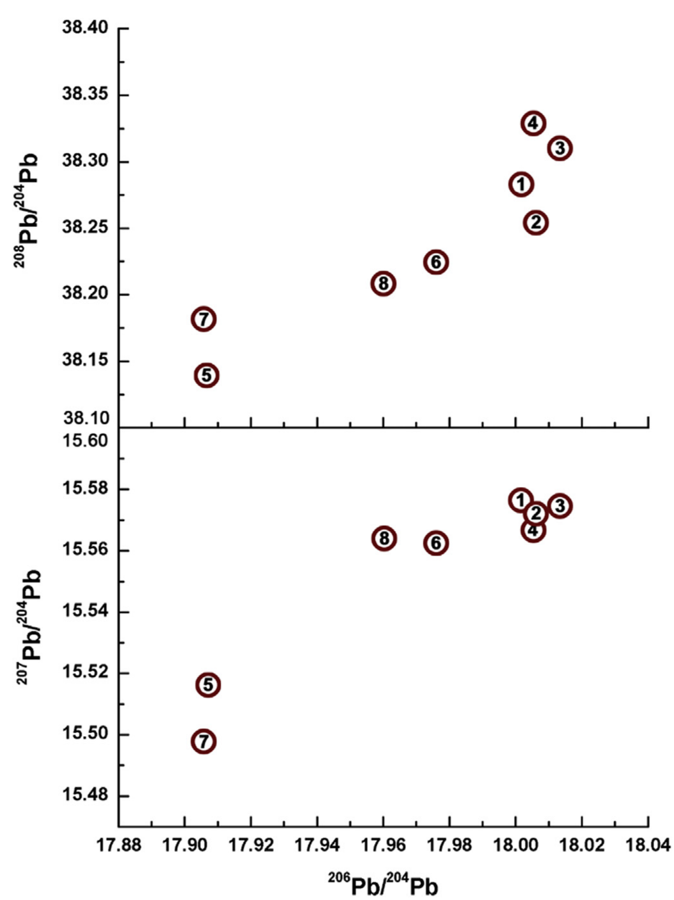

Fig. 7. Graphical presentation of lead isotope ratios of the eight samples.

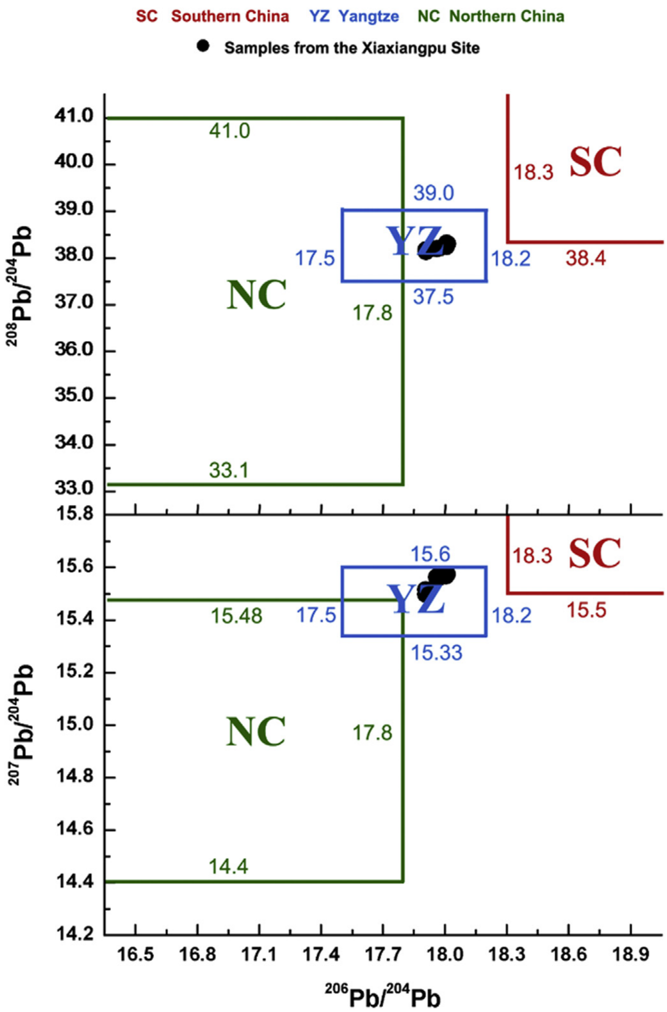

Fig. 8. Comparison diagram based on lead isotope ratio ranges of geochemical province Southern China, Yangtze, Northern China (after Zhu, 1995).

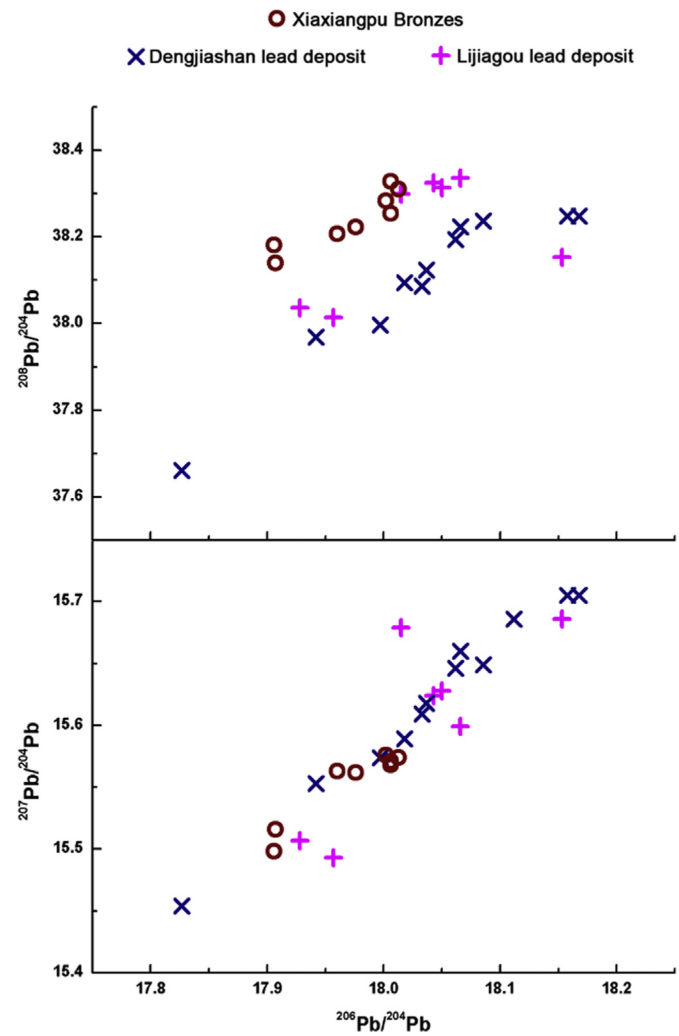

Fig. 9. Lead isotope ratios of the Xiaxiangpu bronzes and isotope ratios of potential ore sources in Gansu (data sources: Qi, 1993).

lead deposit are as high as the Xiaxiangpu bronzes. If the lead ores around Longnan City, Gansu Province were considered as potential sources for the Xiaxiangpu bronzes, then the ores from the Lijiagou lead deposit are the most likely sources of the lead used to make the bronze artefacts.

3.3. Relevant historical and archaeological issues

In 1942, a Ding vessel was found in Fufeng County, Baoji City, Shaanxi Province. This Ding vessel is widely known for its 207 character inscription. The 207 words tell the history about the fall of the state of E. It is called “Yu Ding”, because its owner was “Yu”, according to its inscriptions. After repeated studies, historians and archaeologists considered that Yu Ding belonged to the period of King Li (c. 878–841 BC). The inscriptions say Yu served the State of Jing. There are almost no written records in literature of the state of Jing. By studying inscriptions on bronze vessels, historians and archaeologists considered that the state of Jing was in Shaanxi Province, and the nobility of Jing were offspring of the Zhou royal court. Yu ordered troops to crush down the rebellion leaded by Marquis E, and then Yu made a Ding vessel as a souvenir. The inscriptions on the Yu Ding indicate the states in the northwest of China already had military power to conquer the old states in central China in the period of King Li (c. 878–841 BC) (Li, 1984; Chen, 1959; Xu, 1959). In the period of King Xuan (c. 827–781 BC), the state of Shen was removed to Nanyang to defend the border for the Western Zhou Dynasty. It means that although the state of E survived in the war, it had lost the power to defend the border (Chen, 2006, 1989; He, 1983).

The comparison of the Xiaxiangpu bronzes with bronze artefacts from Gansu Province, Shaanxi Province and Shanxi Province shows many overlaps (Fig. 10) (Jia, 2010; Jin, 2008). The Xishan site is in Lixian County, Longnan City, Gansu Province; the Bianjiazhuang site is in Longxian County, Baoji City, Shaanxi Province; the Chencang site is in Baoji City, Shaanxi Province; and the Qucun site is in Quwo County, Linfen City, Shanxi Province (Fig. 1). The bronze artefacts collected from Bianjiazhuang, Chencang and Xishan belonged to the state of Qin in the late Western Zhou Dynasty to the early Eastern Zhou Dynasty (c. 885–650 BC). The bronze artefacts collected from Qucun belonged to the state of Jin in the same period (Jia, 2010; Li, 2010; Jin, 2008).

It might not be a coincidence the lead isotope ratios of the Xiaxiangpu bronzes partially overlap the ratios of the bronze artefacts excavated in northwest China. After the state of E was defeated by troops from the northwest, it might have become economically subservient to the states in the northwest. As was mentioned above, the lead ores used for the eight samples of the Xiaxiangpu bronzes might come from the area around Chengxian

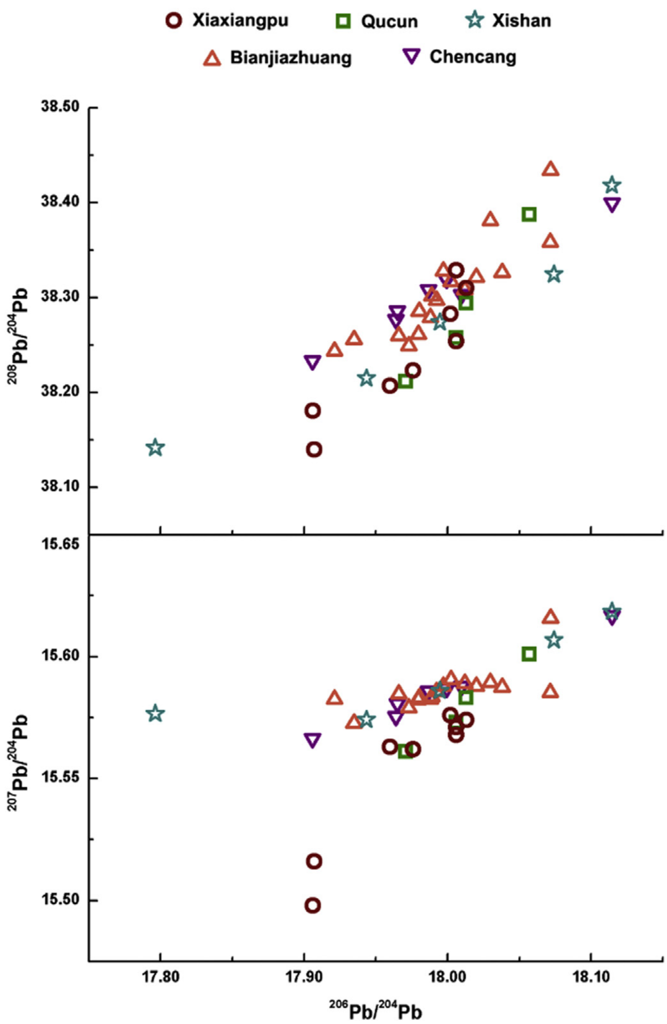

Fig. 10. Lead isotope ratios of the Xiaxiangpu bronzes and bronzes from archaeological sites of Qin and Jin in the turn of the Western Zhou Dynasty to the Eastern Zhou Dynasty (data sources: Jia, 2010; Jin, 2008).

County, Longnan City, Gansu Province. The Chengxian County is close to Lixian County, Longxian County and Baoji City, and this region was under the control of the state of Qin in the Zhou Dynasty. It could be that the bronze artefacts of Qin could be produced with lead ore sources that are locally available. Lead ores or cast bronze artefacts were exported to other places such as E and Jin. The lead ores or cast bronze artefacts could be exchanged as prestige goods, tribute or war trophies.

4. Conclusions

Eight bronze samples from the Xiaxiangpu site, representative of the state of E in the turn of the Western Zhou Dynasty to the Eastern Zhou Dynasty (c. 885–650 BC), were analysed for elemental concentrations and lead isotope ratios. The elemental concentrations show the lead should be introduced on purpose, and the lead isotopes represent the provenance information of lead ores. The lead isotope ratios conform to the characteristics of common lead, which supports the hypothesis the bronzes with low $^{207}Pb/^{206}Pb$ ratios between 0.70 and 0.78 gradually disappeared during the Zhou Dynasty in Henan Province, central China. The isotope ratios of the eight samples fall into a small area in the diagramme. Though sample XXP05 and XXP07 appear in an area which is distinct from the group of the other six samples, all these samples may have a single lead ore source. Lead ores from the area around Chengxian County are the most likely sources of the lead used to make the Xiaxiangpu bronzes. According to historical documents, the state of E was defeated by troops from the northwest of China. The comparison of the Xiaxiangpu bronzes with bronze artefacts from Gansu Province, Shaanxi Province and Shanxi Province shows many overlaps. After the state of E lost its power, it might have become economically subservient to the states in the northwest. The lead ores used for the Xiaxiangpu bronzes might come from the state of Qin. The same lead ores might also be used by the state of Qin itself and the state of Jin. Lead ores or cast bronze artefacts were exported from Qin to other states such as E and Jin. However, the lead ores or bronze artefacts could be exchanged as goods, tribute or war trophies, and the reasons for exportation remain an open question.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2014.09.021.

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